Renewable and Sustainable Energy Reviews 33 (2014) 214–223

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Current status and potentials of enhanced geothermal system in China: A review

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ARTICLE INFO

Article history:
Received 15 April 2013
Received in revised form
27 December 2013
Accepted 29 January 2014
Available online 26 February 2014

Keywords:
Enhanced geothermal system
China
Renewable energy
Geothermal gradient
Potential assessment

ABSTRACT

This research focuses on the enhanced geothermal systems (EGS) potential in China and related technology, especially induced microseismicity and carbon storage combination. Hydraulic fracturing mechanisms applied in EGS were compared with similar fracturing mechanisms for shale gas. Besides, geothermal gradient in China was mapped based on the most recent heat flow values with interpolation method. The development history of geothermal plants in China was comprehensively reviewed through case studies. This paper revealed that the geothermal measuring wells in China were too shallow and too few to offer an accurate estimation. A coming work should aim at heat flow survey in deep layer, induced microseismicity mechanisms, and economically feasible scope in China. These problems will strengthen practical understanding and facilitate extensive application of EGS in China.

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http://dx.doi.org/10.1016/j.rser.2014.01.074
1364-0321

1. Introduction

With the fast economic development in China, the demand for energy grows rapidly. In 2011, China contributed 71% of the increase in the world energy consumption, and according to the recent report [1] China was ranked first in the total energy consumption of the world. In the energy composition of China, coal-fired power was still the primary energy source and its percentage was about 81.3% in 2010 [2]. The combustion of coal, however, produces large amounts of carbon dioxide, sulfur dioxide and nitrogen oxides, which definitely do harm to human health and ecological environment. As for the other main fossil fuels, China imported 252.9 million tons of crude oil (which constituted 54.76% of the total oil consumption in China [1]) to satisfy the increased demands. The excessive dependence on such imported energies is detrimental to the economy, politics, ecological environment and national security of China.

To obviate or alleviate the over-reliance on conventional energies, China invested heavily in the renewable and sustainable energy such as wind power and solar power particularly in the past decade. Up to 2012, China had cumulatively installed wind turbine capacity of 62,412 MW (MW), ranked first in the world. The cumulative installed solar photovoltaic (PV) power in China was 3000 MW in 2011, an increase of 275% compared to the year 2010. In contrast, the installed geothermal power capacity in China was only 24 MW which remained unchanged for nearly two decades, far less than the capacity of U.S., 3112 MW in 2011 [1]. This great contrast is shown in Table 1.

As we see from Table 1, China was the lowest one among five selected nations not only for the percentage of geothermal energy in the total renewable energy, but also for the net amount of geothermal energy. The geothermal energy was used widely in China, but mainly for direct-use applications such as spas and residential heating. Statistics [3] showed that in China the total direct use of geothermal energy in 2010 was 75,348.3 TJ, which was the largest amount in the world. These statistics indirectly reflect that geothermal energy potential has not been fully exploited yet in China, especially as some important usages such as electricity generation.

In fact, geothermal utilization and geothermal plants are not new in China and their history can be traced back to 1970s [4]. However, most of the plants were shut down years later due to corrosion and clogging of the pipeline. So far, only the Yangbajing power plant is still running and generates nearly 24 GW per year. As shown in Fig. 1, it indicated that geothermal power only takes 0.0013% in the primary energy production in China. The delay in the development of geothermal power in China was attributed to the high initial cost and the limited technologies in China.

Enhanced geothermal system (EGS) represents a series of technologies, including resource exploration, hydraulic fracturing, directional drilling, and seismicity monitoring methods. Traditional hydrothermal power plants generate electricity by exploiting the natural hot water in the geothermal fields. However, in some geothermal fields, the temperature of deep rock is high, but its permeability is low, or the formation lacks enough stored water, which is unfavorable to energy production. In this case, various engineering methods are applied to increase the permeability and expand the heat transfer area in the reservoir. For instance, cool water is injected to stimulate a man-made reservoir and the heated water is used to generate electricity. Overall, by EGS, the productivity of an existing geothermal power plant can be increased and more geothermal fields, which are traditionally viewed unsuitable for power generation, can be developed commercially.

With great potentials, EGS also has some problems. To clarify EGS technological and economical feasibility, and to evaluate EGS potential in China, this study reviewed the status of research about EGS induced microseismicity [5–11] and the feasibility of using CO_2 as a working fluid [12–18]. According to geothermal gradient map and geological conditions in China, recommendations and directions for EGS development in China were provided at last.

Table 1
Cumulative installed renewable energy capacity (MW) and percentage of geothermal energy in total renewable energy in 2011 [1].

2011	China	U.S.	Italy	Japan	Mexico
Wind	62412	47084	6743	2595	1123
Solar	3000	4389	12782	4914	41
Geothermal	24	3112	863	502	887
Percentage (%)	0.037	5.701	4.233	6.267	0.432

2. EGS projects and technologies in the world

2.1. EGS projects in the world

Since the first hot dry rock (HDR) project in Fenton Hill [19], more and more countries have initialized their research and development on EGS. Among the EGS projects, some famous ones are listed in Table 2.

The experiences of existing EGS projects are constructive for future research and development. For example, through the Fenton Hill [19] project, it showed that the stimulated rocks usually fracture along the least principal stress direction. In addition, the Fenton Hill project indicated that building only one production well near a single injection well could be tremendously wasteful. As a result, later projects often applied two or more production wells around an injection well to make full use of the injected fluids. However, a comprehensive optimization on the distance between an injection well and the production wells is often necessary. When the distance is long, the heat transfer areas are huge, leading to high geothermal mining productivity. In contrast, when the distance is small, the water loss can be reduced further [26]. It needs to search for an optimization point between geothermal mining productivity and water loss rate. Besides, other difficulties may be encountered in these projects, such as the relative locations between the well and the fault, the precipitation problems, and so on [27]. The most critical difficulty, however, was the induced

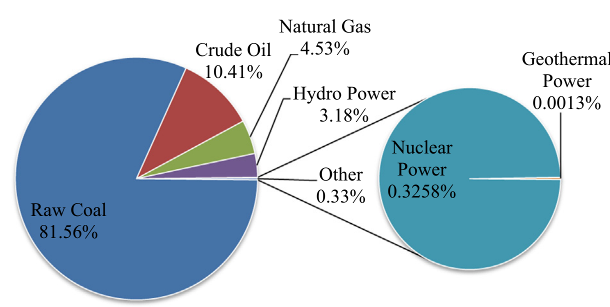

Fig. 1. Composition of primary energy production in China (2010) (Data from [2]).

Table 2
EGS projects in the world.

Country	Project	Temperature (°C)	Gradient (°C/km)	Maximum depth (km)	Plant type	Capacity (MW)
U.S.	Desert peak [20]	196	178	1.1	Binary	11–50
France	Soultz [21]	200	100	5	Binary	1.5
Japan	Hijiori [22]	270	123	2.2	Binary	0.13
Australia	Cooper basin [23]	250	57	4.4	Kalina	25
Germany	Gross Schoenebeck [24]	149	35	4.2	Binary	0.75[25]

Table 3
Seismicity in EGS projects.

Project	Magnitude	Depth	Temperature (°C)	Max. injection rate (L/s)
Basel [5]	3.4	5	< 200	50
Soultz [30]	2.9	5	202	80
Cooper Basin [9]	3.7	4.4	–	48
The Geysers [8]	4.4	3	240	347
Berlin, El Salvador [31]	4.4	2.5	305	200

micro-seismicity [9], since it greatly raised social concern about the security of EGS.

2.2. EGS induced microseismicity

The induced microseismicity is not unique to EGS. In fact, the induced seismicity has been reported due to deep mining at Gazli of Uzbekistan [28], a huge dam at Koyna of India [28], and subsurface nuclear explosion.

The EGS induced seismicity raised great social concern in Basel. In 2006, two seismic activities with magnitude of 2.7 and 3.4, respectively, occurred in the urban area of Basel [5]. Due to their small magnitudes, no structure damages happened in the city, but EGS was suspended permanently in Switzerland. Fortunately, numerous statistics obtained in Basel provided sufficient raw data for scientific research. Actually, a large number of earthquakes happened in the recorded history of Basel. In 1356, the most significant earthquake recorded in Central Europe occurred in Basel [29]. From 1980 to 2004, the recorded seismic activities larger than magnitude 2.0 accumulated to 21 times [5]. Studies showed that the micro-seismic events were very common in the history of Basel [9], implying that the micro-seismicity was not caused by drilling and stimulating of EGS. However, the micro-seismicity happened to most extent naturally. Refer to Table 3 for the earthquake data of several EGS projects.

Numerous studies on the mechanism of the induced earthquakes have been conducted [5,8–10]. The occurrences of an earthquake were often the consequence of multiple factors. The intrinsic factors include the relative positions between boreholes and faults, the mechanical properties of discontinuities, the stored tectonic geology stress of surrounding rock, the fault length, and the vibration frequency when destroyed [9]. The extrinsic factors include the magnitude of temperature difference, the pressure of injected water, the water injection rate, and the used chemical reagents.

Generally, two factors were viewed more important than others for the induced seismicity. One was the decreased effective stress, which is caused by the increased pore pressure [5]. To be specific, at the initial stage, the fragile discontinuities in rock masses are readily impaired by water, leading to the lowered friction at the interfaces of blocks, and then the effective stress between the faults will decrease with the increased pore pressure. Consequently, along the fault sliding, the stored tectonic geological stress is released to cause seismic activities.

The other important factor was thermal stress [32,33]. In the existing EGS projects, many seismic activities happened when water injection stopped. For instance, the maximum seismicity in Berlin of El Salvador occurred two weeks later after the shutdown of water injection. Similarly, the maximum seismicity in Soultz of France happened two days later after the shutdown of water injection [9]. Based on these facts, researchers remarked that after the shutdown of water injection, the water pressure varied a little, but the thermal stress continued to influence the stress distribution. To understand this problem, Ghassemi et al. [33] built a 3-D boundary element model and demonstrated that the thermal stress in the reservoir was ongoing. It kept influencing the delayed rock deformation, which had substantial contribution to the seismicity. As too many assumptions were made in the coupled numerical model for the stress field and temperature field, a practical test is needed to give more accurate results. For instance, hot water and cool water can be injected separately and then the monitored seismicity can be compared and measured to obtain the proportion of thermal stress influence.

Some other factors, such as rock burst [34] due to rock mass removal, the decreased friction coefficient due to chemical corrosion, also contributed to the occurrence of seismicity. Generally, researchers considered that the occurrence of micro-seismicity is not caused by oversize water pressure directly. Actually, the microseismicity is closely related to the fault sliding. Though the impact of different factors is uncertain, all these factors have close relationships with the pre-existing faults. In later projects, if the relationship between the well location and fault are tackled appropriately, the seismicity could be controlled within acceptable limits. Hence, if low-grade geothermal fields are farther away from the pre-existing faults than high-grade geothermal fields, the risk of low-grade fields would be lower. Therefore, this kind of low-grade geothermal fields may be more suitable for heat exploitation. Additionally, only when the seismicity size is large enough and near the urban or industrial facility does microseismicity cause damage to human. Hence, by taking this social risk into consideration, the EGS projects should be developed in remote areas first, and in future national code, the secure level should be stricter in residential areas than in open fields.

With a comprehensive understanding of the geological condition and a reasonable selection of the field, the microseismicity can be controlled or even avoided. Moreover, reasonable microseismicity could be beneficial to the monitoring of reservoir engineering. For instance, seismic monitors combined with a network can be utilized to decide whether water injection in Berlin of El Salvador should continue [24].

2.3. Utilization and storage of CO_2

To cope with the global warming and lower the carbon emission, various methods for carbon capture and storage were developed [35]. In the natural gas mining process in Sleipner, Norwegian, one million tons of carbon dioxide was injected into the deep saline aquifers [23]. In Weyburn, Canada, carbon dioxide was injected to enhance the oil mining, and about 2 million tons of carbon dioxide was disposed every year [36].

When using water as a working fluid, a large amount of water runs off during the EGS operation process, which is a serious problem, especially in dry areas. Using CO_2 instead of water as a working fluid can effectively avoid this problem, which was originally proposed by Brown [15]. Afterwards, Pruess [17] built a mathematical model through the software TOUGH to evaluate the feasibility of CO_2. The simulation showed that CO_2 has many advantages over water in the heat mining process. For instance, because the density of heated CO_2 in production wells is about half of the density of injected CO_2, so less gravitational potential energy is wasted in the rising process. In contrast, the liquid water does not possess this advantage as its density remains almost constant during the process. In addition, CO_2 is a non-polar molecule so that it will not react with surrounding rocks and equipment materials, leading to a saving in corrosion prevention. The disadvantage of CO_2 is its low specific heat capacity; however, the higher mobility of supercritical CO_2 compared to water can compensate this deficiency, and numerical modeling [17] showed that the heat mining efficiency of CO_2 is about 2–5 times of water. Besides, when using water as a working fluid, the heat mining efficiency may decrease with the depletion of geothermal energy, while this situation is not evident when CO_2 is utilized. Some numerical modeling indicated that when CO_2 is used, the heat mining efficiency increases in certain pressure instead [18], since lower temperature increases the density of CO_2 and enhances its mobility, while the mobility of liquid water remains constant with temperature varying.

One extra benefit of using CO_2 is the carbon storage capacity. Due to the high temperature and high pressure in the geothermal wells, the carbon storage rate is higher than normal oil and gas wells. According to the numerical modeling, the carbon storage rate is about 1 kg/s per MW [13], which is impressively high. For example, the carbon storage rate of a 3 MW CO_2-EGS plant is close to the specialized carbon storage site in Mongstad, whose rate is about 3.17 kg/s in Phase 1 [37]. To validate the feasibility of carbon storage in CO_2-EGS, field experiments in Ogachi geothermal field [14] were conducted and the process was monitored. Water with different concentrations of CO_2 was injected into the well, and the monitored data showed that the Ca^{2+} concentration became higher with the increased concentration of CO_2 in water. Consequently, $CaCO_3$ precipitation was observed in the well, indicating that CO_2 can be captured and stored by EGS.

Furthermore, recent research [38] showed that carbon storage in rock is helpful to reduce the seismicity risk, because the precipitation caused by CO_2 will increase the contact areas between rock grains, then reduce both the local shear and normal stress, and eventually shrink the Mohr circle not to reach the Mohr–Coulomb failure envelope. However, in heat mining process, not specialized for carbon storage, the precipitation may not only occur on the edge of the reservoir, but also inside the working wells. To understand this process, numerical modeling [16] showed that although the precipitation caused by CO_2 will clog the low-salinity reservoirs in less than 25 years or the high-salinity reservoirs in less than 1 year, the clogging often occurs at some very specific areas of the wells, so that measures can be taken to alleviate or even prevent this clogging possibility.

2.4. *Comparison with shale gas*

Directional drilling and hydraulic fracturing play important roles in the exploitation of EGS [39–41] and shale gas [42–46]. However, fracturing mechanism and environmental impact are different between the two types of projects.

2.4.1. *Different fracturing mechanism*

Shale usually does not have sufficient permeability to allow significant fluid flow to a well bore [47]. Shale gas is one kind of unconventional natural gas. The storage space is mainly the cracks among shale rocks [48]. In most cases with low pressure and low saturation level, the productivity of shale gas is low. In some fractured regions, however, the output is high enough for commercial exploitation [49]. To fracture shale rock, it creates new fractures and opening through the injection wells, which increases the rock's permeability and productivity [50]. In this process, rock may fracture when water pressure is larger than the minimum principal stress of rocks. The fracture is oriented perpendicular to the minimum principal stress [51]. Therefore, tensile stress is the critical factor for the occurrence of new cracks.

For EGS, propagation of preexisting fractures is usually the main part in fracturing process, such as Soultz project [52–54]. Some other EGS fracture is the combination of preexisting fracture extending and new cracks, such as Fenton Hill EGS project [55,56]. Since preexisting fracture zone is much weaker than intact rock, the water pressure of hydraulic fracture in EGS is lower than that in shale gas exploitation.

2.4.2. *Impact on water quality*

Shale gas need not only water, but also chemical additives [57]. For instance, in fracture process, it need prop materials, such as silicon sand, man-made ceramic, to keep the fracture open when water pressure is reduced. Later, before production stage, the prop materials should be cleaned by physical or chemical process. Moreover, to carry these prop and prop-killing materials, it should add chemical additive, such as polymer, to improve the water viscosity [58]. Eventually, 50–70% of water and chemical additives will be retrieved [59]. The impact of remained chemicals on ground water is uncertain. Some researchers showed that leaked nature gas and chemicals may pollute the ground water [59–64].

In EGS, since required injection pressure is low and heat is the extraction target, no chemical additives are required in the fracturing process [65]. Water is the only injection materials. It will not harm the environment. In arid areas, however, the natural water is in short supply. Water-intensive industry may seriously impact local ecosystem [66].

3. Development status and potential of geothermal energy in China

China has paid great attention to the development of renewable energy. In recent years, the renewable energy production rises quickly. Geothermal energy, has been widely used in China, but traditionally limited to the direct use such as spas and residential heating instead of electricity generation. With the development of EGS in the world, more and more scholars and politicians in China have refreshed their view of geothermal power [67].

3.1. *Geothermal power in history*

In 1970s, a number of low-temperature small hydrothermal power plants were built throughout China mainland [68]. However, due to pipeline clogging and low temperature in shallow wells, most of them were shut down a few years later [4]. These projects are listed in Table 4.

To some extent, the shutdown of these sites was attributed to the negative influences of "Cultural Revolution" and limited drilling equipment at that time. Hence, some of these sites still have the potential of the geothermal power through exploring deeper wells and hotter rocks. Generally, the underground temperature rises with the depth increasing, but in a varied increasing rate. Hence, although the

Table 4
Geothermal power plants in Chinese history.

Project site	Province	Depth (m)	Temperature (°C)	Power (kW)	Year
Dengwu, Fengshun county [69]	Guangdong	300	92	300	1970
Huitang, Ningxiang county [70]	Hunan	182	98	300	1972
Houhaoyao, Huailai county [4]	Hebei	288	87	240	1971
Tangdongquan, Zhaoyuan county [4]	Shandong	300	98	300	1972
Xiongyue, Gai County [71]	Liaoning	176	90	100	1982
Reshui village, Xiangzhou City [4]	Guangxi	120	79	200	–
Wentang, Yichun county [72]	Jiangxi	300	67	100	1971

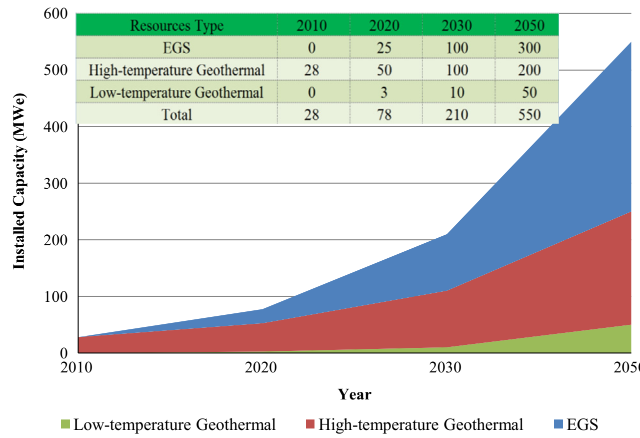

Fig. 2. China Geothermal Power Development Goals (Data from [76]).

temperature listed above was not economical for electricity generation since the wells were shallow at that time, further exploiting deeper wells in these sites may provide high temperature and sufficient geothermal resources commercially.

3.2. *Geothermal energy and national policy*

Some national standards and regulations in China, which are favorable for geothermal energy, have been published. In 2006, "People's Republic of China Renewable Energy Law" came into effect [73]. This law defines the geothermal energy as a renewable energy. Moreover, according to the national standard GB11615-89 "Geologic exploration standard of geothermal resources" [74], Chinese government sets the lower limit of geothermal resources at 25 °C and defines the geothermal anomaly zone in a plain region where the thermal gradient ≥ 3 °C/100 m. Geothermal anomaly regions are judged suitable for geothermal resource evaluation and further exploration. In 1989, the exploration depth was set to be less than 2000 m due to the technological and economic conditions at that time. In 2010, however, the national standard "Geologic exploration standard of geothermal resources" was revised and the exploration depth was increased to 4000 m [75]. Therefore, more and deeper wells will be drilled to explore the geothermal energy in the future.

In 2011, the Medium-and-long-term (2030, 2050) Development Strategy Study of China's Energy, funded by the Chinese Academy of Engineering (participated), was promulgated [76]. It is expected that until 2050 China's renewable energy can meet 43% of country's total energy needs. According to the requirements of Chinese Academy of Engineering, Geothermal Committee of China Energy Research Society undertakes the Medium-and-long-term Strategic Discussions of Geothermal Resources, and the development goals are illustrated in Fig. 2.

3.3. *EGS potential assessment*

All high-temperature geothermal fields in the world are located along the plate edges, while a few are located in intraplate rift zones (such as East African Rift Valley) or hot spot (Hawaii). China has rich geothermal resources. The average heat flow in China mainland is 61 ± 15.5 MW/m^2, ranging from 30 MW/m^2 to 140 MW/m^2 [77]. According to the theory of plate tectonics, southwest China is compressed by the Indian Ocean plate, southeast China is compressed by the Philippines plate and east China is under the compression of Pacific plate, and all of these regions have intense geological activities and high geothermal gradients, such as Yangbajing in Tibet, Tengchong in Yunnan, North Hainan, Taiwan, southeast coastal areas and Heaven Pool in Changbai Mountains [77].

3.3.1. *Geothermal gradient*

The potential of EGS in China is assessed here with a comprehensive geological analysis. As the thermal conductivity of rock can be improved through engineering methods, the geothermal gradient rather than heat flow is used to assess the EGS potential. Data are taken from the global heat flow database of the international heat flow commission [78], and both Asia data and Former Soviet Union data are referred to in evaluation of China's geothermal gradient. The measurement points, which lack the geothermal gradient, are removed. Based on these data, the grids of the geothermal gradient are displayed in Fig. 3, in which the inverse distance weighted method is used as the interpolation method. From Fig. 3, it is noted that some areas in Tibet, Yunnan and Shanxi province have a high geothermal gradient. It should be mentioned that the some potential places lack enough measurement wells (Fig. 4) to judge the geothermal potential, especially in Guangdong, Hainan and Taiwan Province. However, these three provinces, located at the junction of the Pacific Plate and the Eurasian Plate, have abundant geothermal energy. For example, the first hydrothermal power plant was built in Fengshun county, Guangdong Province [79]. In Fig. 4, one may be surprised to notice that no measurement wells data in Tibet are observed. In fact, all the geothermal wells in Tibet are shallower than 1000 m, which are not shown in Fig. 4. Nonetheless, the geothermal power plants in Tibet have worked in good conditions for decades since the hydrothermal energy is extremely abundant.

According to the MIT Geothermal Electric Evaluation Model (GETEM) [80], a high-grade geothermal field (Geothermal gradient > 80 °C/km) is economical at the current level of technology. Obviously, based on the existing data of shallow wells in China only a few measurement points located at Tibet, Yunnan and southeast coastal areas meet this standard. When the economical standard becomes applicable to the middle-grade geothermal field (Geothermal gradient > 50 °C/km), more places will be included in the list with the potential to develop EGS. The places with the geothermal gradient larger than > 50 °C/km are marked in Fig. 5.

It should be noted that the economical standard mentioned above was proposed based on the level of technology in U.S. However, when it is applied to China, the extra cost for research or technology purchase should be considered.

3.3.2. *Potential sites for enhanced geothermal system*

Since the underground temperature rises with the depth increasing, theoretically the EGS can be applied throughout the continent. However, due to the limitations in the drilling technology and economic factors, EGS can only be exploited commercially

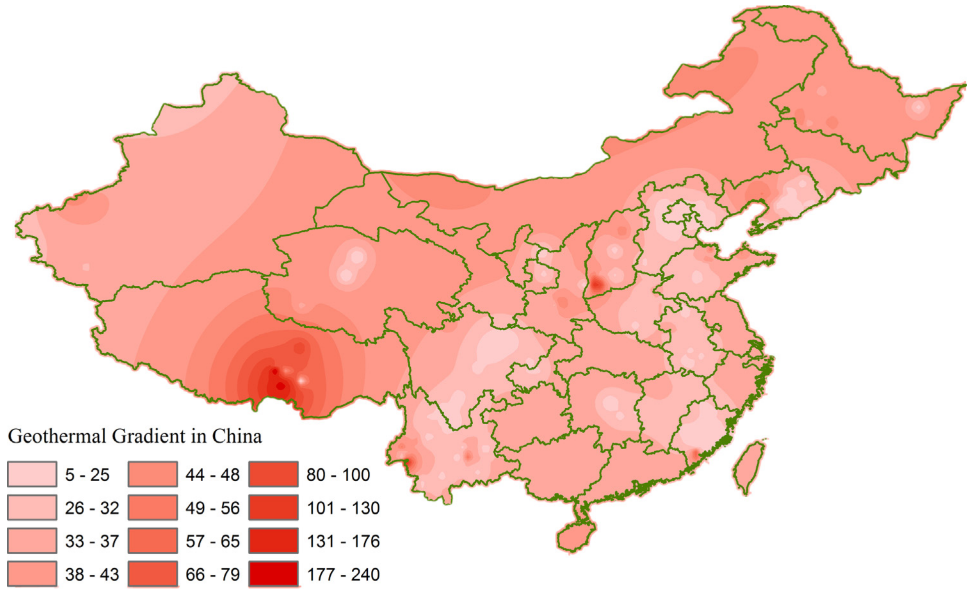

Fig. 3. Geothermal gradient in China (°C/km) (Data from [78]).

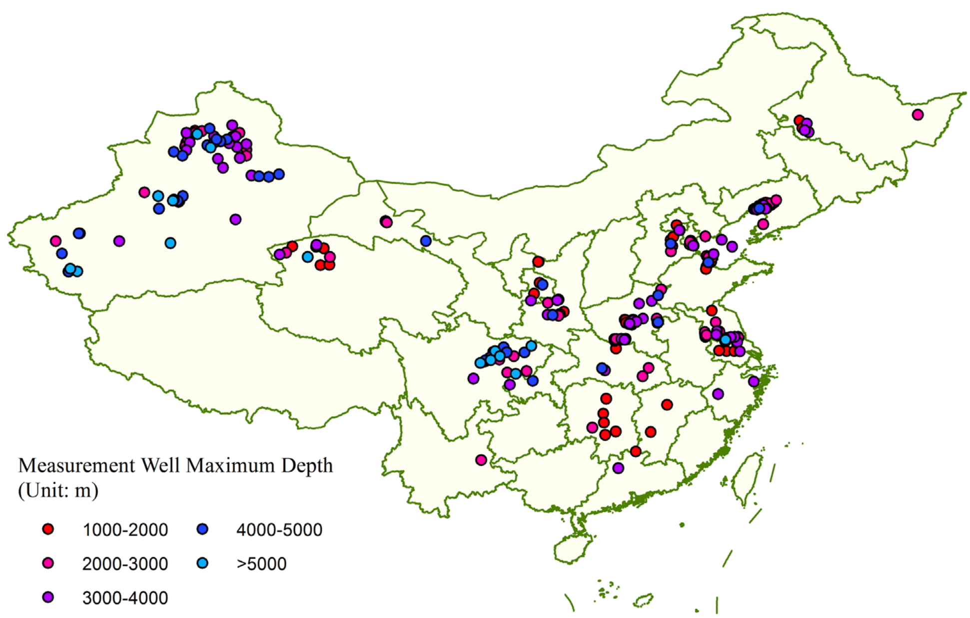

Fig. 4. Measurement well maximum depth (Unit: m) (Data from [78]).

in certain places with high geothermal gradients. In the monitored places of China, some potential places for EGS are listed in Table 5.

3.3.3. Discussion

Since 1979, China has drilled 862 heat flow measurement wells, among which 823 wells are accurate and available [77]. The number of measurement wells is too small compared with 4249 wells in America [78]. Most of heat flow measurement wells in China are less than 1 km, and about 40% wells are less than 0.5 km [77]. Moreover, the wells deeper than 1 km are mainly located at several places, such as Junger, Erdos, and Tarim. In contrast, EGS is able to exploit the geothermal energy with the depth of 3–10 km. The existing measurement wells were too shallow to evaluate the EGS potential in China. Though deeper heat flow values can be estimated by the corresponding shallow wells, the estimation value is inaccurate, because the geothermal gradient in shallow subsurface is influenced by the past atmosphere conditions [82]. Hence, shallow wells can't reflect the heat flow values accurately in deep layers, depending on geological conditions. As a result, more deep measurement wells are in great need to evaluate the EGS potential in China.

As for the small number of measurement wells, the reason was that most wells were built in the past decades [4] and at that time, drilling technology in China was limited. Additionally, due to the blind development of geothermal plants by local governments without consideration about the local geothermal potential, and due to the low energy conversion efficiency at that time, many projects were shut down eventually [68]. These failed projects made some people believe that geothermal energy is merely

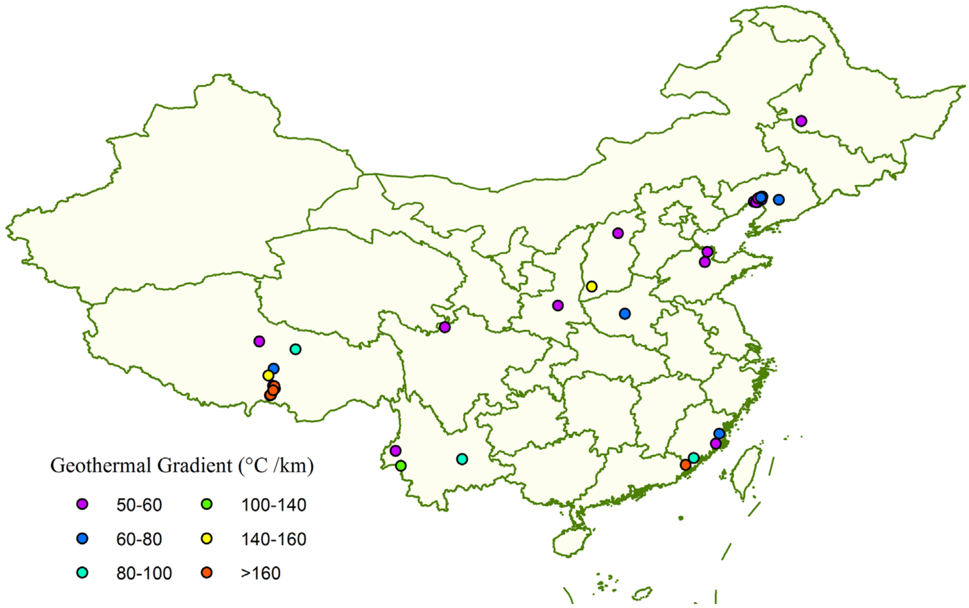

Fig. 5. Sites of geothermal gradient >50 °C/km (Data from [78]).

Table 5
Potential sites for EGS in China.

Potential site	Geological characteristics	Geothermal data	Pre-existing hydrothermal plant	Location
YangbajingTibet	Indian Ocean Plate drifts northward and has collision with the Eurasian Plate, resulting in the Tibet region uplift and abundant geothermal energy	The temperature in 1800 m is more than 300 °C. The average geothermal gradient is 100 °C/km	Operation 24 MW	In rural area
Tengchong, Yunnan	Tengchong locates in southeast Tibet, belong to Mediterranean – Himalayan – Southeast Asian volcanic belt. [81] Geothermal resources are ensured by the magma intrusion and volcanic eruptions in deep mantle	The heat flow is 118.0 mW/m^2, and the average geothermal gradient is 46 °C/km [50]	No	In urban area The spas are abundant
Guangdong	Geothermal resources in Guangdong Province is in zonal distribution and is controlled by magmatic rocks and faults	The temperature is 92 °C in 300 m	Suspended in 2008[51]	In urban area The spas are abundant
Hainan	Leiqiong in Hainan has abundant Cenozoic volcanic rock distribution in South China coastal region. The volcanic area reaches 7000 km^2	The average heat flow is 87.07 mW/m^2 More measurement wells are needed	No	Undeveloped

suitable to direct use, rather than to electricity production. To avoid the same old road, before EGS extensive application in China, it is recommended to build a heat flow database and establish the economically feasible scope in China. To enrich this database, the existing heat flow measurement wells may be sufficiently utilized. Besides, the wells data in oil and gas industries can be collected. In this way, it will save huge money to drill new wells.

4. Proposals for EGS development in China

Obviously, China will need more and more energy to prompt her rapid economic development, which, however, has been seriously affected by the pollution due to the dependence on fossil energy consumption. With no doubt, strategy and national policy on renewable energy definitely help change this situation. Compared with wind and solar PV energy, geothermal energy may not be uncompetitive in cost in the long run. According to the total system levelized cost as shown in Fig. 6 provided by U.S. Department of Energy in 2012 [83], at the current technology level in US, the geothermal energy cost is \$98.2/MW h, which is almost same to the cost of traditional coal based plant—\$97.7/MW h. Though the geothermal related technology is limited in China and the corresponding technological cost is higher, geothermal resources are abundant and underdeveloped in China. Therefore, through

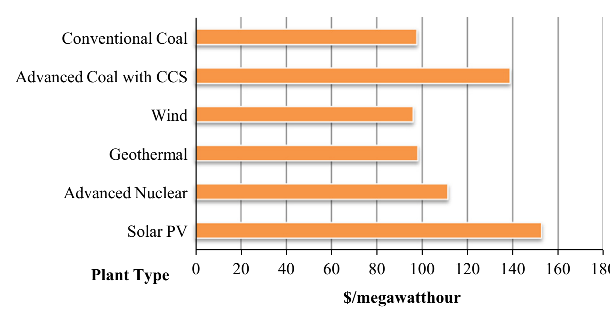

Fig. 6. Total system levelized cost by energy resources in U.S. (Data from [83]).

years of technology development, it is economical for China to develop geothermal plants in the long run.

As we noticed, the reliance on coal and oil in China has caused significant damage to the environment and economic developments. In 2011, the amount of CO_2 emission was 8979.1 million tons, ranked the top one in the world [1]. With the calculation, \$50 for per ton of CO_2, estimated by Tol [84], the economic loss caused by CO_2 in China was about 6.13% of GDP in 2011 [2]. If the economic loss caused by pollution is added into the cost of coal-fired power, the middle-grade geothermal exploitation will become more competitive.

In the management of energy utilization, some views should also be changed to contribute to environment protection. For instance,

most residential heating in Beijing still relies on coal burning, so that lots of non-renewable resources are wasted and the environment is also polluted, although some of which has been replaced by the combustion of nature gas. It is safe to say that the eye-catching high concentration of PM2.5 (particulate matter with the diameter of 2.5 micrometres or less) in Beijing and Shanghai has substantial relationship with the large amounts of coal burning [85]. Compared to the consumption of coal and natural gas, heat pump is an appropriate selection for the metropolises in China.

Apart from direct use, geothermal power also has a unique advantage. Compared to wind power and solar photovoltaic power, geothermal energy is steadier regardless of weather conditions. Compared to the other base load suppliers, such as coal-fired power and nuclear energy, which are all harmful to the environment, geothermal energy are environment friendly as base load [80].

Some specific recommendations are thus listed as follows.

- Geological exploration—especially the fault and earthquake in history
  The existing measurement wells nowadays in China are insufficient and not deep enough. According to the revised national standard "Geologic exploration standard of geothermal resources", the exploration depth has been extended to 4000 m [75]. With deeper wells and more collected data, more accurate and comprehensive assessments can be provided. Furthermore, if oil and gas well data are also collected, the assessments will become better. During the exploration, besides the essential thermal data, the fault conditions and recorded earthquakes should also be collected for evaluating the seismicity risk.
- Geothermal plant experience—the coproduced plant and geopressured field
  To accumulate geothermal plant experience, co-generation based on abandoned mine wells can be developed in some areas, especially in North China Plain such as Dagang oil field [86] and Liubei-qianshan oil field [87]. Many oil fields in North China Plain were reported having hot water with temperature higher than 100 °C [88]. These abandoned oil fields may be utilized to produce electricity. This coproduced plant can avoid the exploration risk and save upfront drilling cost. Additionally, geopressured fields may be developed to test the geothermal equipment as well as the geothermal power plant, and in geopressured fields, mechanical energy, thermal energy and mineral energy can all be exploited [89]. In China, some places, such as central Guanzhong basin [90], possess the potential of developing geopressured fields. Considering the economic factors, these geopressured and coproduced fields may be explored in near future. In this process, the adopted geothermal technologies, such as reservoir engineering, hydraulic fracture and horizontal drilling, and associated risks in these fields are similar to those of EGS. Through these projects, dependable equipment and experienced teams will become more mature for future EGS.
- EGS technology development—CO_2 storage
  With the advances of technology and large-scale production, the geothermal exploitation cost will be reduced to half and soon a quarter [80]. As we know, the per capita water resource of China is only 25% of the world average [66]. Furthermore, the water distribution is spatially unbalanced so that some regions are seriously in short of water especially in potential EGS sites like Tibet. The large amount of carbon emissions is another potential risk in China. Hence, the carbon storage technology, associated with EGS, deserves more attention. In this process, a multi-physics analysis is particularly valuable.
- EGS demonstration plant—Yangbajing, Tibet
  Nowadays, the installed hydrothermal power capacity in Yangbajing is 24.18 MW, which generates nearly 100 million kW h per year. An EGS model in Yangbajing has been proposed [91], and it is estimated that 1000 MW installed capacity can be achieved through three wells with the depth of 9000 m. It should be mentioned that any seismicity events during the drilling and stimulation process should be monitored to accumulate data for future developments. Besides, the cost and profit with time should be recorded to establish economically feasible scope of EGS in China. The advantages of Yangbajing come from not only the abundant geothermal resources, but also the supporting facilities for power generation and transportation on the ground. Hence, the upfront cost for ground facilities can be saved. In Tibet, Cuoqin basin [92] and Qiangtang Basin [93] have hydrocarbon potential, and thus the produced CO_2 in these fields may be stored in Yangbajing EGS as the working fluid.
- Reservoir monitor method
  The related monitor method should be developed and enhanced. In EGS, common monitor method includes wellbore stress tests, ultrasonic borehole televiewers, acoustic emission, and temperature survey. Among them, acoustic emission is the best method to monitor the drilling and reservoir conditions [94,95]. Multiple acoustic emission probes are able to locate the position and intensity of acoustic emission. Compared the acoustic emission data with historical statistics, it enhances our understanding on the connectivity between wells, the positional relationship with faults [96]. These monitor data are helpful to hydraulic fracturing process, such as to determine the pressure and rate of water injection. On the other hand, acoustic emission is virtually same to seismic waves. The analysis of acoustic emission helps to control the earthquake risks. Artificial intelligence (e.g. artificial neural network algorithms) is able to learn the data and to avoid the induced earthquake [97]. The monitor technique is same to the exploitation of shale gas. During the exploitation of shale gas in China, it should enhance the related monitor technique for future EGS.
- Numerical modeling technology
  A good numerical model is quite helpful to the establishment of EGS. To model EGS fracture process, multi-physics phenomenon is indispensable, because thermal stress is huge and not ignorable. Besides, since rock fractures in the construction stage, the classical theory of continuum mechanics, which is based on partial derivatives, brings many singularities on crack surfaces [98–100]. Hence, it is hard to simulate the fractures with classical method. The peridynamic theory is based on integral equations, which avoids the difficulties in partial derivatives. Moreover, peridynamics is able to incorporate chemical reaction easily because the breakage force of chemical bond can be calculated directly. However, this method is immature because the computation cost is too huge. To model EGS accurately, peridynamics and other related numerical methods, like multiscale modeling and thermal–hydrologic–chemical coupled mechanism should be developed [101,102].

5. Conclusions

5.1. Key limitation of EGS

The key limitation of EGS is induced seismicity and tremendous initial cost. To mitigate earthquake risks and wells drilling cost, a comprehensive geological survey is indispensable. Besides, an advanced monitor method is also crucial to the establishment of EGS. Therefore, the related materials and technology, such as measurement wells, hydraulic fracturing, and acoustic emission monitor in oil and gas industry, should be collected to promote EGS development in the future.

5.2. Promising alternative technology for EGS

To develop EGS in arid areas, the utilization of carbon dioxide as working fluid is promising and technically feasible. Besides, some research showed that a part of carbon dioxide was stored in working process, which fill up cracks and mitigate earthquake risks. However, to stimulate EGS reservoir, water is the main stimulating fluids. It is hard to use carbon dioxide to displace water totally in this process. More research should be carried out in this direction because it is quite helpful to climate as it combines renewable power generation and carbon storage together.

5.3. Recommendations for China

For the similar cost of drilling deep wells, it is economically favorable to develop oil and gas wells first. Moreover, for oil extraction and heat extraction, most exploitation techniques are same with each other, like hydraulic fracturing, directional drilling, and acoustic emission monitor. Therefore, China should invest in the practical exploitation of shale gas and shale oils, and meanwhile invest in the related research of EGS. In addition, it should be noticed that shale gas is not renewable and its environmental impact is inevitable. Conversely, EGS, as a renewable and sustainable base load, is environmental friendly. To initiate EGS in China, a demonstration project of EGS should be built in China, and Yangbajing is the best place for demonstration site because it has abundant geothermal resources, existing hydrothermal wells, and existing ancillary facilities.

Coproduced geothermal power plants based on abandoned mining wells and geopressured fields may be developed in advance to prepare for EGS technologies, to accumulate research data and to train inexperienced teams. As we suggested, more and deeper geothermal measurement wells should be built for evaluating the geothermal potential in China. Meanwhile, the high-temperature drilling technology and seismicity data should be collected for further development. The monitor method, like acoustic emission, should be developed to improve the understanding of reservoir conditions. Multi-physics numerical simulations should also be carried out to explore and evaluate the applications of using CO_2 as a working fluid.

Acknowledgements

The research is supported in part by the scientific research foundation for the National Basic Research Program of China, No. 2012CB026104, by the Fundamental Research Funds for the Central Universities, No. 2013JBM059, and the Program for Changjiang Scholars and Innovative Research Team in University (PCSIRT, IRT1029).

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